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ANALYSIS OF THE EFFECTS OF FREE STREAM GAS VELOCITY UPON ASTRONAUT THERMAL COMFORT

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OBJECTIVES

The Analytical Section of the ECS Branch of the Crew Systems Division has performed a study to investigate the effect of free stream gas velocity upon astronaut performance. The ultimate objective of this investigation was to determine the minimum free stream velocity that can be tolerated by man in a zero gravity environment, assuming a reasonable range of possible cabin environmental conditions and crew activity levels.

INTRODUCTION

A free stream velocity of the atmosphere surrounding man provides two principal functions: (a) removes the products of metabolism and (b) provides metabolic heat rejection.

Carbon dioxide and water are the two major by-products of metabolism in man. It is necessary to remove these wastes from the immediate vicinity of the man so that he can continue functioning normally. To a certain extent, normal gaseous diffusion will accomplish this function. However, the diffusion mechanism is limited and for metabolic rates higher than sedentary, a free stream gas velocity must be provided.

Thermally, a free stream gas velocity provides convection cooling and evaporation of moisture released as "sweat" by the man. For high

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Thermally, a free stream gas velocity provides convection cooling and evaporation of moisture released as "sweat" by the man. For high activity rates, latent evaporation is often a principal means by which man dissipates metabolic heat. Since diffusion alone cannot provide adequate mass transfer under these circumstances, a free stream velocity becomes mandatory. Of course, the magnitude of required latent evaporation heat removal is a function of all of the environmental parameters affecting crew thermal comfort: atmospheric free stream velocity, pressure, cabin gas temperature, cabin dew point temperature, and cabin wall temperature. For the purposes of this study, it was assumed that the cabin wall temperature would not be below 55°F (to prevent water condensation on the wall) and that cabin dew point temperature would not exceed 60°F. Furthermore, the analysis considered cabin pressures of 5 psia 10 psia, and 14.7 psia. One additional constraint placed upon the problem required that body skin temperature be maintained above 88°F, since lower temperatures induce discomfort. This last constraint places a restriction on the amount of radiation heat transfer to which the crewman can be subjected.

Phase I concerned itself with the determination of free stream velocity existing under sea level conditions due to the atmospheric motion induced by (1) the temperature gradient between the man and the atmosphere and (2) the gravity field. It is expected that this velocity, which can provide thermal comfort under one-g at 14.7 psia, produces a thermal dissipatory effect which, if duplicated at 5 psia under zero-g will result in an acceptable velocity environment.

Phase II employed the use of the NASA-MSC Transient Metabolic Load Analysis computer program. This program has the capability of predicting human thermal comfort under a variety of environments and considers the effect of free stream gas velocity on both convective and evaporative cooling.

Finally, Phase III consisted of a literature search of manned chamber tests evaluating human thermal comfort zones at reduced pressures. The analysis and results of the study follow.

ANALYSIS AND RESULTS

I. Correlation of "Free Convection" Flow to a Forced Velocity Field

Phase I of the analysis investigates the nature and significance of free and forced convection and evaluates their dependence upon velocity. Where a gravity field exists, such as on earth, there will be fluid motion around a man if his surface temperature is at a temperature different from that of the atmosphere surrounding him. This is caused by density gradients between the atmosphere near the man's skin surface and that removed from him. These gradients create buoyant forces. The buoyant forces result in fluid motion with consequent convective heat and mass transfer taking place. The force of gravity is thus the driving force which produces the atmospheric motion and maintains a "free convection" process continuously around a man on earth. Therefore, this motion is always providing a minimum free stream gas velocity to maintain physiological well-being as previously discussed (i.e., providing convective cooling, evaporative water removal, CO_2 removal, etc.). It might be added that, in many situations on earth, man is not content with this "free convection" and thus artificially supplies a more "comfortable" forced convection field.

In the zero gravity space environment, free convection doesn't exist. Therefore it should be of benefit to determine the forced convection required to provide the condition which exists on earth.

If one were to characterize man as a cylinder with a gas stream flowing parallel to his body (a perpendicular flow assumption does not give significantly different results), the Nusselt number (N_{nu}) for forced convection may be written:

1) $Nu_{\#} = (h_{forced}\ L/k = .664 \quad (\rho VL)/\mu)^{\frac{1}{2}} \quad (Cp\mu)/k)^{\frac{1}{3}}$

The free convection N_{nu} may be similarly written:

2) $Nu_{\#} = (h_{free}\ L)/k = .67 \left(\frac{Pr}{Pr + .952}\right)^{\frac{1}{4}} \left(Gr \cdot Pr\right)^{\frac{1}{4}}$

where ρ = gas density, lb/ft^3
V = gas velocity, ft/min
L = plate or cylinder length, ft.
k = gas conductivity, Btu/hr-ft °F
μ = gas viscosity, lb/ft-hr
Cp = specific heat, Btu/lb-°F
Pr = Prandtl number
Gr = Grashof number
h = heat transfer coefficient, Btu/hr - ft^2 - °F

Utilizing the properties of air (or oxygen) and considering the body dimensions of an average man, and setting equations 1 and 2 equal, we get

3) $.0212\ (PV)^{\frac{1}{2}} = (.06) \quad (P)^2\ g(Ts - Ta)^{\frac{1}{4}}$


RANGE OF ATMOSPHERIC VELOCITIES UNDER SEA-LEVEL CONDITIONS
VELOCITY (FT/MIN)
50
40
30
20
10
0
0
5
10
15
20
SKIN TEMPERATURE — ATMOSPHERE TEMPERATURE, °F

Figure 1

where P = pressure, psi
g = fraction of earth gravity
Ts = body skin temperature, °F
Ta = cabin gas temperature, °F
V = gas free stream velocity, ft/min.

which reduces to

$$4)\ V = \left\{ .06 \ \frac{P^2 g\ (Ts - Ta)}{.0212\ P^{\frac{1}{2}}}^{\frac{1}{4}} \right\}^2$$

We can solve equation 4 by assuming that a comfortable sea level environment is one in which the temperature difference between skin* and atmosphere is 20°F. Furthermore, we can say a slightly uncomfortable environment exists when $T_{skin} - T_{air} = 10°F$, and finally, a moderately uncomfortable or stuffy environment exists at $T_{skin} - T_{air} = 5°F$. These three rather reasonable situations should illustrate the velocity range normally experienced at sea level, and are shown in Figure 1. It will be noted that the velocity ranges from 15 to 35 ft/min.

Although the above results may be indicative of the range of velocities of interest, the importance of velocity on the affected parameters (i.e., heat transfer, evaporation, etc.) has not been established on earth. Therefore no correlation about that velocity required for the space application at reduced pressure and that required on earth can be made at this time. It is first necessary to consider the actual thermal balance of a crewman in a spacecraft environment. Therefore, these results must not be interpreted to be indices of thermal comfort.

* Skin temperature is normally near 93°F.

II. Computer Simulation

The next phase of the investigation employed the use of the NASA Transient Metabolic Load Analysis computer program. The program analytically simulates the thermal response of man to his environment as a function of his metabolic activity level in significant detail. The simulator considers the internal physiological response (core temperature, blood flow, respiratory rate, etc.) of the man, resulting in sweating rate, shivering rate, heat storage, etc., as well as the external heat transfer mechanisms taking place between the man and his environment through convection, radiation, and evaporation.

Computer simulations were made at 5 psia and 14.7 psia. The 5 psia cases considered wall temperatures from the lower limit of 55°F* to a nominal value of 75°F. Furthermore, cabin gas temperatures over the range 70 to 75°F and dew point temperatures of 55 to 60°F were used. In addition, several metabolic rates were considered. The 14.7 psia run was performed to correlate the effect of 1 "g" free convection with forced velocity effects for typical sea level conditions at various metabolic rates. Figures 2 to 5 are plots of body heat storage vs. velocity for steady state conditions.**

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* A 55°F lower limit wall temperature was chosen to prevent water condensation on the wall.

** Some mention should be made of the use of body heat storage as the significant comfort parameter. Under conditions of thermal comfort, average skin temperatures are approximately 93°F and average deep body temperatures are approximately 98.6°F. The total heat storage resulting from these temperatures rising significantly above their norm values is considered an accurate appraisal of thermal comfort. Heat storage values in excess of 300 Btu's are equivalent to running a moderate "fever" and result in decrements in performance; heat storage values in excess of 400 Btu's are equivalent to a higher body temperature with a possibility of heat exhaustion or collapse.

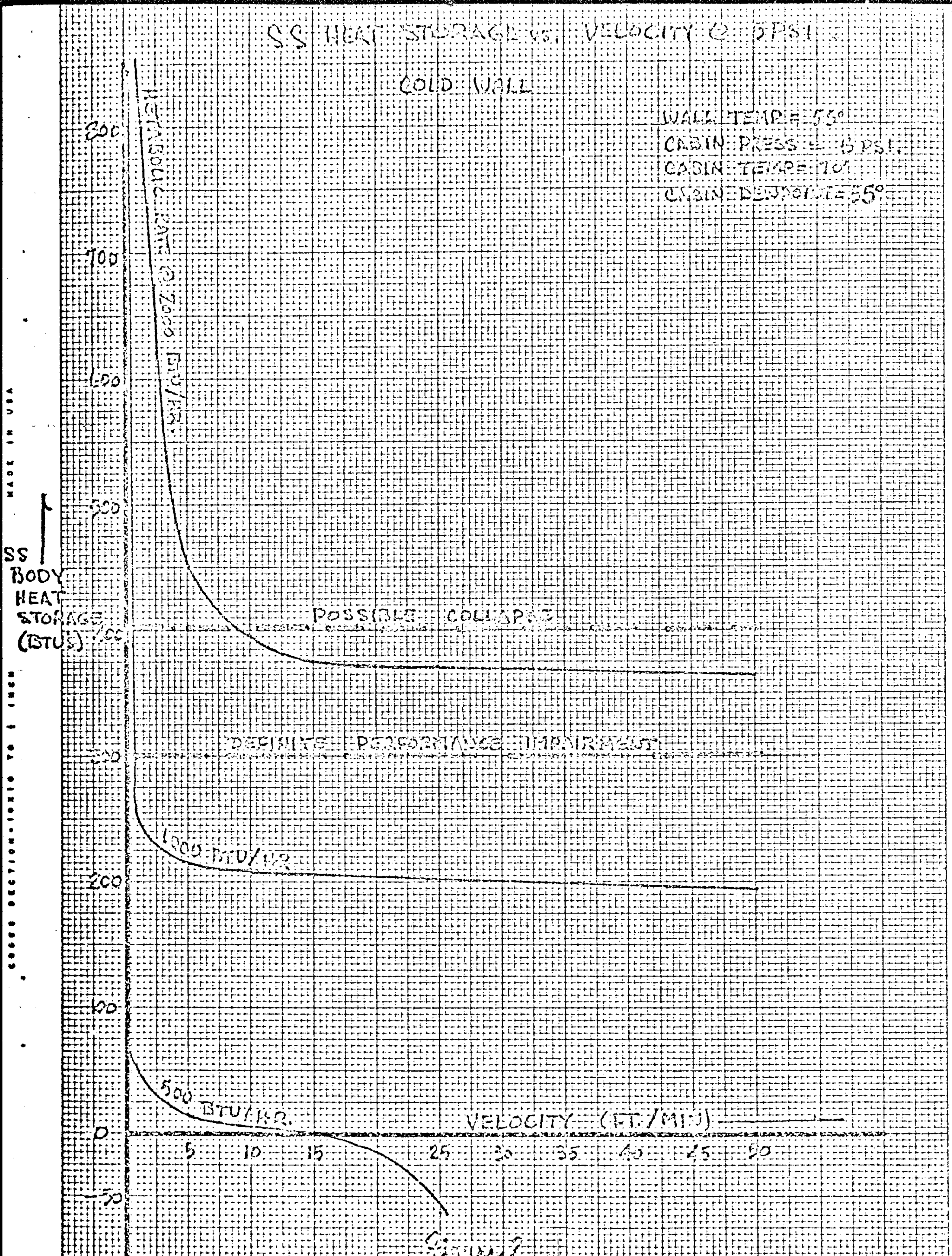
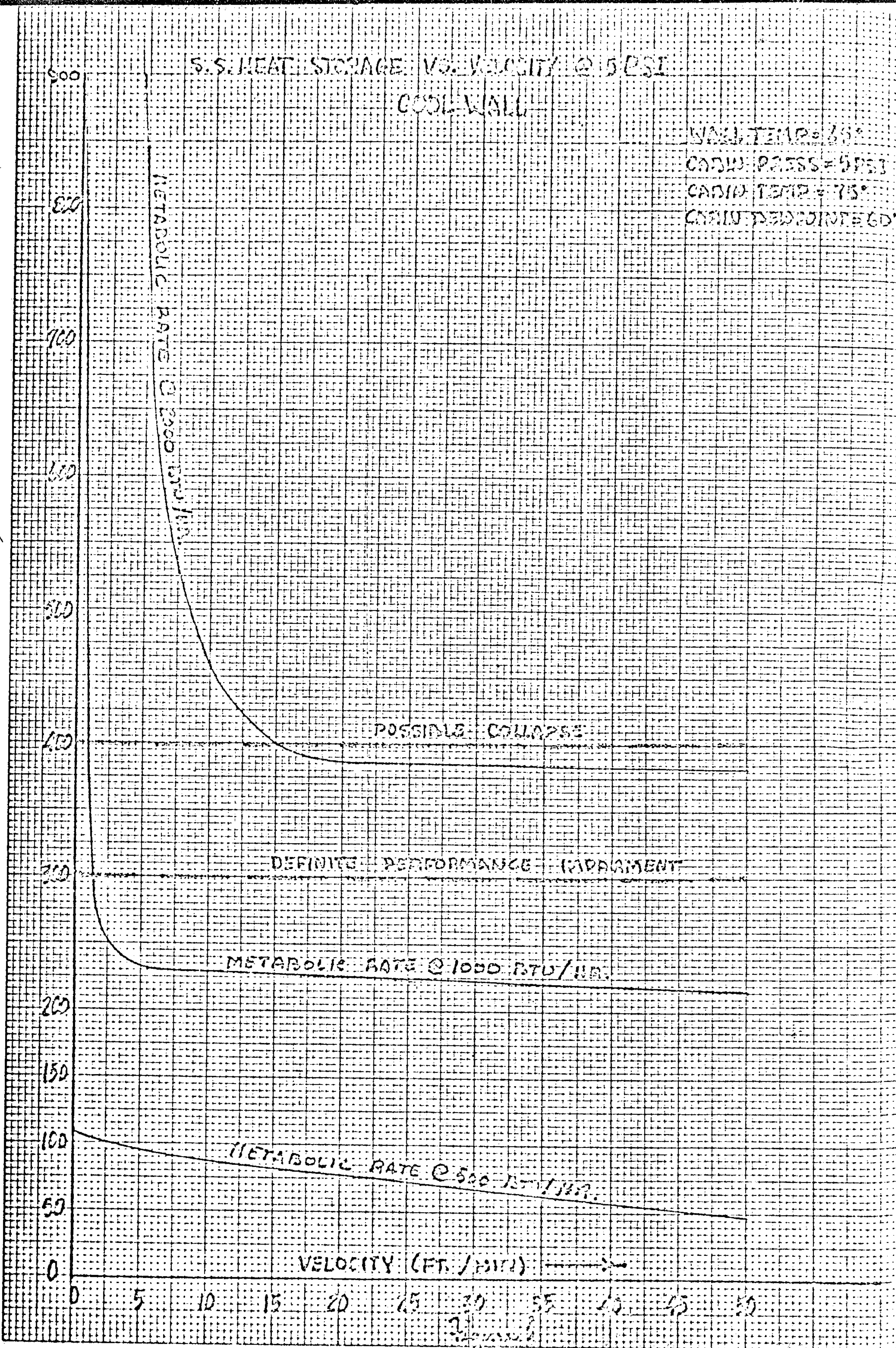
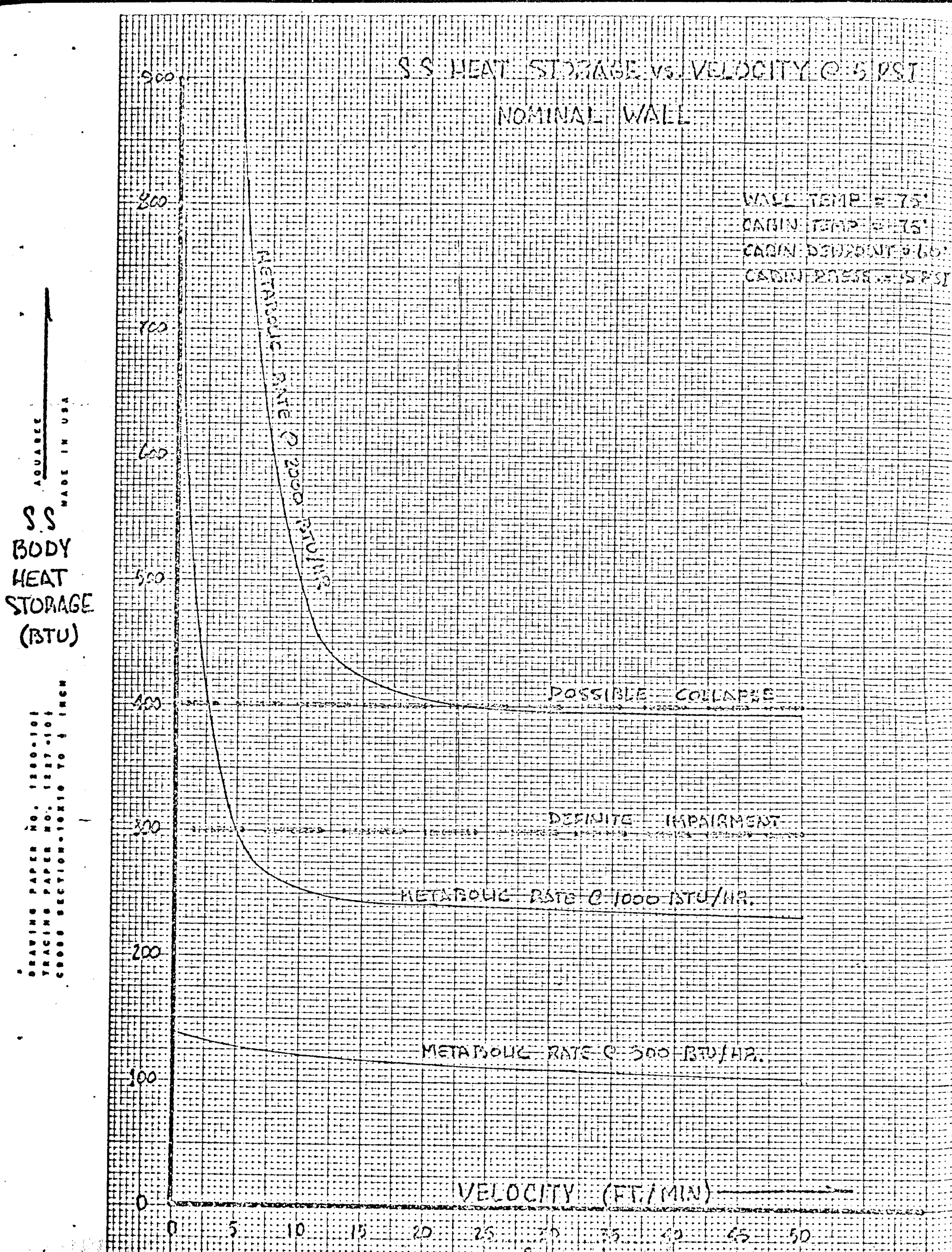

SS HEAT STORAGE vs. VELOCITY @ 5 PSI
COLD WALL
WALL TEMP = 55°
CABIN PRESS = 5 PSI.
CABIN TEMP = 70°
CABIN DEWPOINT = 55°
SS BODY HEAT STORAGE (BTUS)
800
700
600
500
400
300
200
100
0
-50
METABOLIC RATE @ 2000 BTU/HR.
1000 BTU/HR
500 BTU/HR.
POSSIBLE COLLAPSE
DEFINITE PERFORMANCE IMPAIRMENT
VELOCITY (FT./MIN)
5
10
15
25
30
35
40
45
50

Figure 2



S.S. HEAT STORAGE VS. VELOCITY @ 5 PSI
COOL WALL
WALL TEMP = 35°
CABIN PRESS = 5 PSI
CABIN TEMP = 75°
CABIN DEWPOINT = 60°
S.S. BODY HEAT STORAGE (BTU'S)
METABOLIC RATE @ 2000 BTU/HR.
POSSIBLE COLLAPSE
DEFINITE PERFORMANCE IMPAIRMENT
METABOLIC RATE @ 1000 BTU/HR.
METABOLIC RATE @ 500 BTU/HR.
VELOCITY (FT./MIN)
0 5 10 15 20 25 30 35 40 45 50
900 800 700 600 500 400 300 200 150 100 50 0


S.S HEAT STORAGE vs VELOCITY @ 5 PSI
NOMINAL WALL
WALL TEMP = 75°
CABIN TEMP = 75°
CABIN DEWPOINT = 60°
CABIN PRESS = 5 PSI
S.S BODY HEAT STORAGE (BTU)
METABOLIC RATE @ 2000 BTU/HR.
POSSIBLE COLLAPSE
DEFINITE IMPAIRMENT
METABOLIC RATE @ 1000 BTU/HR.
METABOLIC RATE @ 300 BTU/HR.
VELOCITY (FT./MIN)
0
100
200
300
400
500
600
700
800
900
0
5
10
15
20
25
30
35
40
45
50
AQUAREE
MADE IN USA
DRAWING PAPER NO. 1280-101
TRACING PAPER NO. 1227-101
CROSS SECTION-10X10 TO 1 INCH
Figure 4

S S HEAT STORAGE vs. VELOCITY @ 14.7 PSI
NOMINAL WALL

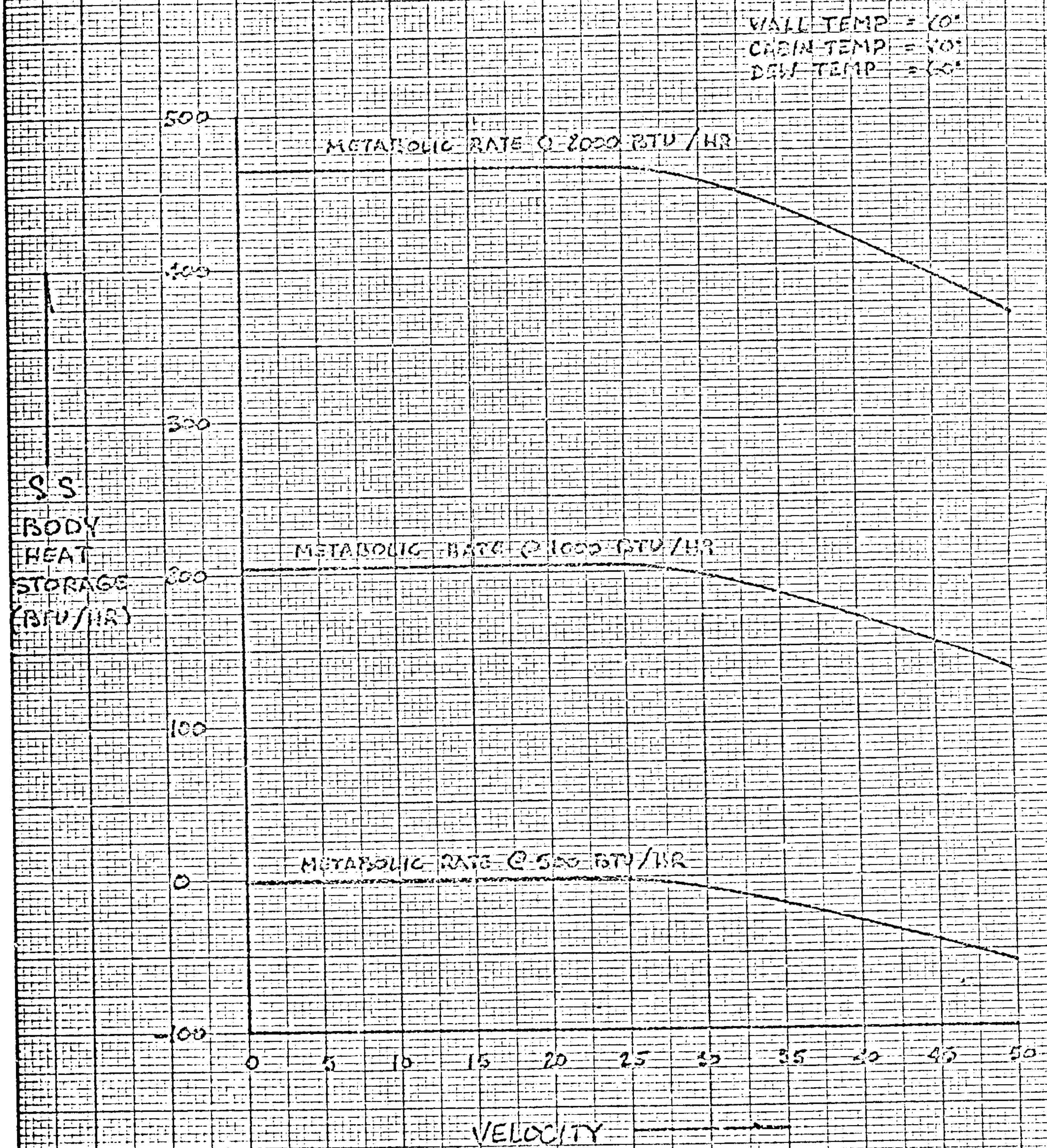


Figure 5

Of primary interest is the shape of the curves in Figures 2, 3, and 4. As stated in the introductory comments, diffusion alone does not provide adequate moisture removal. This effect is shown quite dramatically at the lower velocities. Heat storage rises exponentially since inadequate mass transfer does not dissipate the latent heat generated at high metabolic rates. As the velocity increases, mass transfer increases until all of the latent heat generated by the man is evaporated. At this point, the curves flatten out and it can be seen that the gradual decrease is due to convection cooling alone which is not very significant for the velocity range considered. Therefore, it may be concluded that the importance of velocity in maintaining the thermal balance of a working crewman stems primarily from water removal, not convective cooling.

The significant results of this portion of the analysis show that for periods of high activity (2000 Btu/hr metabolic rate), velocities of at least 15 ft/min are required to remove the latent heat of evaporation generated and thus maintain body heat storage below the point of possible collapse even with the lowest wall temperature. For the higher wall temperatures, periods of high activity would result in definite performance impairment and possible collapse if sustained for any length of time unless velocities near 25 ft/min are provided. However, for the high wall temperature case, periods of moderate activity (1000 Btu/hr) could be safely tolerated with cabin velocities of 15 ft/min. For resting periods (500 Btu/hr or less) diffusion is sufficient. It should be noted that the most desirable thermal condition (zero heat storage) occurs for a sedentary crewman with a cold wall and a velocity of 15 ft/min.

A run at sea level conditions was made to compare the results from the transient metabolic simulator with the Phase I results which indicated free convection equivalent velocity to be 15 to 35 ft/min. Figure 5 shows that heat storage is dependent only on free convection until forced convection effects begin to dominate at velocities greater than 25 ft/min. This suggests that free convection currents at sea level generate equivalent velocities in the neighborhood of 25 ft/min, which is in basic agreement with the results of Phase I of this study (see Figure 1). This result of velocity equivalence could have been anticipated since (1) it has been determined that evaporation is the dominant effect and (2) evaporation is controlled by water vapor removal, which is a function of volume flow (and thus proportional to velocity).

III. Literature Search

The final segment of the study was a literature search to determine any qualitative velocity effects that might exist. The most pertinent documentation that could be found was a report of a manned chamber test to determine thermal comfort zones for mixed atmospheres at reduced pressures. The investigation was performed by Douglas Aircraft Corporation under Contract NASW-1371. The study was actually intended to determine the effect of reduced gas thermal conductivity upon comfort; however, it coincidentally provided some insight into the effects of gas velocity. The significant result of this test was that subjects at 5 psia experiencing velocities of 20 ft/min required lower limit comfort temperatures significantly below those of subjects exposed to velocities of 50 and 80 ft/min. One series of runs indicated that a minimum temperature of 71°F was selected by subjects at 5 psia to keep them comfortable. This would seem to suggest that to maintain comfort with velocities below 20 ft/min, the environmental control system would have to be capable of providing cabin temperatures below 70°F. Of course, the chamber tests in the Douglas study were all made at 1 "g" and the effects of free convection on the results cannot be underestimated.

Other interesting results of the literature search disclosed that 20 ft/min was usually the minimum velocity utilized in chamber tests because (a) this was believed equal to minimum natural convection currents, and (b) this was the minimum velocity observed to maintain "air freshness" over subjects participating in tests.

CONCLUSIONS

When on earth, man is provided with a natural flow of atmosphere about his body induced by the existing gravity field. Under normal sea level conditions this natural flow provides about a 20 to 30 ft/min atmospheric velocity. This, of course, does not establish the necessary flow for crew survival under spacecraft conditions.

Consideration of the overall thermal balance of a man subjected to spacecraft conditions yields the result that the critical parameter is the removal of the water released by the man for heat rejection. Even for a cold walled vehicle (55°F.), in order to provide sufficient atmospheric flow under high metabolic activity levels (up to 2000 Btu/hr), a minimum velocity of 15 ft/min is necessary to reject the man's latent heat (sweat). For a more normal situation where wall temperature approaches gas temperature, a velocity of 25 ft/min is required at high activity levels. Incidentally, these required atmospheric velocities under spacecraft conditions are very near those provided naturally under sea level conditions as previously discussed.

To obtain further qualitative evidence as to the required velocities, a literature search of available test data on the subject was conducted. Although no really applicable data was found, that available disclosed that a velocity near 20 ft/min is usually considered a minimum for crew comfort during chamber tests.

In view of the above conclusions, specific recommendations are made in the following section.

RECOMMENDATIONS

Based on the results of this study, the ECS Branch of Crew Systems Division recommends that:

- As a design goal, spacecraft should be supplied with ventilation systems capable of providing average free stream gas velocities of approximately 25 ft/min.

- Velocities below 15 ft/min are unacceptable since adequate cooling during high crew activity will not be provided.